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Active Illumination for Robot Vision

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***Abstract*—A vision sensor is the robot's eye to perceive its environment, but the perception performance can be significantly affected by illumination conditions. This paper presents strategies of adaptive illumination control for robot vision to achieve the best scene interpretation. It investigates how to obtain the most comfortable illumination conditions for a vision sensor. In a "comfort" condition the image reflects the natural properties of the concerned object. "Discomfort" may occur if some scene information is lost. Strategies are proposed to optimize the pose and optical parameters of the luminaire and the sensor, with emphasis on controlling the intensity and avoiding glare.**

I. Introduction

MACHINE intelligence increases rapidly when the technology of computer vision is applied because through vision sensors knowledge of the environment can be acquired. Traditional methods for machine vision to better interpret scenes are usually focused on post- image processing (e.g. smoothing, filtering, masking, zooming, contrast stretching, pseudocoloring, etc.). However, post-image processing does NOT increase the inherent information content, but an originally better image contains more information of object surfaces. This facilitates further vision analysis and saves time-consuming enhancement processing, which is very important in a machine vision system, especially for real-time applications.

"As in real estate where the key to successful investments is location, location, location, in machine vision the key to value (equal to success) is lighting! lighting! lighting!", said Nello Zuech, the President of Vision Systems International. The principal reason for success in machine vision is the elimination of appearance variables and the consistent appearance that appropriate, application-specific lighting yields. Unlike the early days of machine vision when many of the entrepreneurial researchers in pioneering machine vision companies suggested, "We just need an image, our image processing and analysis algorithms will work for your application," today people acknowledge the importance of lighting and scene consistency.

The light source for a natural scene is its illumination. For many machine-vision applications, lighting now is the most challenging part of system design, and becomes a major factor when it comes to implementing color inspection. The uniformity and the stability of the incoming lighting are usually the common causes of unsatisfactory and unreliable performance of machine-vision systems. As with any light, illumination has the properties of intensity and color, which significantly affect the performance of robot vision perception as well as human perception.

The selection of light sources and vision sensors constitutes the first problem in vision design. There are many different kinds of sources, including incandescent filament lamps of many kinds, short arc lamps, gaseous and solid-state lasers, fluorescent lamps, high-intensity gaseous discharge lamps, electroluminescent lamps, light emitting diodes, carbon arc lamps, etc. Most CCDs have good red (long wavelength) response, but blue response can be a problem because of absorption in the polysilicon layer that covers the sensitive area. Using back-illuminated sensors may help to avoid this problem. Furthermore, a lot of camera series are ready for industrial use. It is important to select proper parameters, such as focal length, imager size, resolution, angle of view, etc.

Then optical settings and geometrical placements of the light source and the vision sensor become another problem. To solve this, we must firstly analyze what "a perfect image for machine vision" is. A good image means that it contains maximum information about the scene so that the robot can easily understand it. The evaluation criteria of illumination conditions should be given and then the degree of "comfort" to the machine eye may be analyzed.

Effort by Eltoft and de Figueiredo [1] is one of the earliest important attempts in illumination control, and there is other literature with some relations to this problem [2]-[4]. Recently, researchers have become more aware of the subject [13]-[16]. Their work discusses many factors of illumination conditions that affect the quality of the image. However, intensity control and glare avoidance are emphasized primarily in our preliminary work for active illumination setup in a practical vision system.

II. Vision Sensors and Lighting Sources

A. The Machine Eyes

Currently CCD cameras are still the most commonly used

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machine eyes because of their many advantages, although CMOS cameras are also widely used nowadays. Apart from the apparent structure and working mechanism, a machine eye works very similarly to a human eye with some comparable characteristics like resolution, bandwidth, luminosity, the ability to distinguish, adaptivity, and color vision.

For resolution, the ability of human vision to perceive fine detail is called acuity that is expressed as the angle subtended by the smallest object he can discern. For gray-scale objects, this is typically about 1' (minute of arc). A typical camera has an acuity of about 4'. To the human eye's bandwidth, electromagnetic radiation in the wavelength range from 400 to 700nm is what we know as visible light and has peak responsity at 555nm. A typical CCD element (with photodiodes or photogates) is sensitive within a wavelength between 300nm and 1100nm and has peak responsity at 800nm. But it is practically cut off between 400-700nm using filters and normalized to meet the human sensitivity curve.

A human observer perceives the intensity (energy level) of light as the sensation called brightness. However, the perceived brightness varies depending on the color of the light. This is quantified by a luminosity curve. Usually a video camera is designed to have a spectral response that matches the similar luminosity curve. Humans can detect dozens of levels of intensity within a scene, which is referred to as gray-scale response, and thousands of colors. Present common cameras can detect 2^8=256 different gray levels and 2^{24} true colors.

Concerning adaptivity, it is well known that the human eye adapts to average scene brightness over an extremely wide range, as much as 10^{10} to 1. Video cameras are designed to deal with a similar brightness range and provide gray-scale reproduction pleasing to the eye. They use a serial of f-number to adapt to the brightness and at a certain f-number the dynamic range is only thousands of lux.

B. Evaluation of Illumination Conditions

We will now give some quantitative criteria to evaluate the quality of illumination conditions in a specified vision task. These criteria reflect the factors of signal-to-noise ratio (SNR), linearity, contrast, and natural properties of the object.

SNR. SNR is one of the image fidelity criteria that is an important factor in considering illumination control and is measured by determining the amount of random noise on the visual signal in an area of the scene (object). A higher number of SNR produces a picture with enhanced sharpness or other attributes.

Linearity. A typical CCD sensor has a limited dynamic range of illumination intensity. That is, the image irradiance l must lie in the range: $L_{\min} \le l \le L_{\max}$. The contrast compression knee is usually at about 90% *reference white* level, over which it will cause nonlinearity and loss of scene information. Once the white clip level is reached, all color will be lost and the highlight will appear white.

The above interval $[L_{\min}, L_{\max}]$ is called the gray scale. Common practice is to shift this interval numerically to the interval $[0, L]$ by looking it up in the quantization table. l=0 is considered black and $l=L$ is considered white in the scale. However, the *memory look-up table* is not always linear because of transfer-characteristic processes of the camera, such as gain control, gamma correction, and highlight compression. Usually it has better linearity between 5% and 85% of total gray levels, which corresponds to 12 and 216 of 8-bit signal levels.

Contrast. Original contrast is important in machine vision tasks because it means obtaining clear object surface information. Although contrast can also be enhanced during post-processing (e.g. histogram equalization) of the acquired images, original contrast must be good enough so that it survives the quantization process.

Feature enhancement. The features of interest in machine vision include the geometrical object shape and optical surface properties, which both are represented through reflective responsity and the color vector. Therefore, another purpose of illumination control for feature enhancement is to: 1) improve the contrast of reflective responsity, 2) reflect the true color of the object surface. To achieve this purpose, we need to select the proper luminaire type and carefully control luminaire pose, radiant intensity, and color temperature.

C. Controllable Things

1) Brightness

The minimum light input is limited due to the dark current performance of the CCD, which depends on temperature. On the other hand, a brighter scene may bring higher SNR because it contains a larger signal with the same noise and higher image contrast. The basic nature of image brightness $l(x, y)$ is usually characterized by two components: illumination $i(x, y)$ and reflectance $r(x, y)$:

$$l(x, y) = i(x, y)r(x, y). \tag{1}$$

Under the same illumination condition, considering two surface points A and B, it is obvious that larger illumination implies a higher contrast between them because:

$$\text{Contrast} = |l_A - l_B| = i(x, y)|\, r_A(x, y) - r_B(x, y)|. \tag{2}$$

However, too bright an illumination will result in the camera's white balance clipping function and loss of object surface information (both discontinuities and colors).

2) Color Temperature and Color Rendering Index

The color in an image is derived from a complex combination of incoming illumination, material interaction, and detection parameters. The *color temperature* describes the appearance of a light source when someone looks at the light itself and the *color rendering* is given to surfaces when it shines on them.

While the light from a lamp appears white to humans, a color CCD-camera produces a red rich image. This color variation is due to the imbalance of the lamp's spectral output, and it is further exaggerated by the wavelength-dependent sensitivity of a standard silicon CCD sensor, which has stronger sensitivity to red photons than to blue photons. In many color applications, the use of a balanced white light source is preferred in combination with an off-the-shelf single-chip color camera, with RGB output and good long-term stability, providing an optimum balance between color quality and cost.

The *color rendering index* expresses how a light source compares with natural light in its ability to make objects appear in their natural colors. It is a measure of the degree to which the colors of surfaces illuminated by a given light source conform to those of the same surfaces under a reference light. Perfect agreement is given a value of 100%. Common lamps have rendering indices ranging from 20% to 90%. For example, incandescent lamps – 90%, fluorescent tubes – 60-90%, high-pressure mercury lamps – 40-60%, low-pressure sodium lamps – 20-40%.

3) Glare

High contrast between a luminaire and its background may produce glare. A machine eye may not be able to adapt to this situation because it exceeds the dynamic range of the cameras. It is a reason of visual discomfort because the machine eye must handle the highlight. The contrast is degraded when the highlight compression knee is reached and all color and contrast will be lost when white clip levels are reached. In this case, the robot may have difficulty to understand the scene.

Two types of glare are distinguished: 1) discomfort glare or direct glare, resulting in physical discomfort; 2) disability glare or indirect glare, resulting in a loss in visual performance. They will be discussed in the next section.

4) Uniform Intensity

Lighting with uniform spatial distribution is the most efficient solution for a vision system. If the intensity distribution is non-uniform and the pattern is uncalibrated, it will become an additional source of noise and the SNR is degraded.

If the pattern of light source radiation is previously known (through the illumination calibration technique [10]), we may obtain scene features using:

$$r(x, y) = l(x, y)/i(x, y), \qquad (3)$$

where $r(x, y)$ reflects the optical properties (edge discontinuities and colors) of the object.

III. GLARE AVOIDANCE

To the human eye, glare is a source of discomfort because the high contrast between a luminaire and its background exceeds its adaptive dynamic range. This is an even worse situation for the machine eye because the vision sensor has a smaller adaptive dynamic range. Too much illumination volume will automatically cause highlight compression or white clipping. Furthermore, glare usually causes loss of the object's natural color. Hence, two types of glare, disability glare and discomfort glare, should be avoided as much as possible.

1) Disability Glare

Disability glare is usually caused by indirect glare and results in a loss of visual performance. Gudrun [3] concluded that the light color body reflection (diffuse reflection) is determined by intrinsic characteristics of surface materials and the fact that the light color of surface reflection (specular lobe + specular spike) has the same color as the illumination. For example, a shiny red ball will have a specular highlight on its surface only at the position where the ball's curved surface meets the normal reflection condition. The highlight has the same color as the illuminant (white) whereas, at all other positions on the ball, the reflection is diffuse and appears red.

The disability glare light causes two problems. One is that the specular reflection contains only source color, which results in the loss of color rending, causing the robot to have possible difficulty in detecting natural features of its scene. The other is that the highlight usually has a large volume of illumination intensity, which results in highlight compression or white clipping.

Practically, we can avoid the disability glare by presenting the target with light mostly from the side, so that the specularly reflected and hence brightest light is reflected off to the side and away from the field of view.

2) Discomfort Glare

In a lighting system for machine vision, although the main problem may be disability glare, in which the brightness of the luminaires may dazzle and prevent obstructions being seen, we should also consider discomfort glare in the robot environment. It is usually caused by direct glare (due to the lighting installation) and results in physical discomfort.

There are many criteria to evaluate the glare indices. For example, IES Technical Report "Evaluation of Discomfort Glare" [10] sets out the procedure for the evaluation of the glare index in the formula:

$$G_i = 10\log_{10}[0.5\times \text{constant}\sum \frac{B_s^{1.6}\omega^{0.8}}{B_b}\times\frac{1}{p^{1.6}}]. \qquad (4)$$

Recently, the Commission Internationale de l'Eclairage (CIE) established a new glare rating procedure known as the Unified Glare Rating system (UGR) [9, 11] in the form of:

$$UGR = 8\log_{10}[\frac{0.25}{L_b}\sum\frac{L_s^2\omega}{p^2}]. \qquad (5)$$

where p is the positional index.

These criteria are initially proposed for the purpose of human visual comfort. According to the comparison of machine eye and human eye, the CIE-UGR criterion may be adopted for the design of a lighting system in a robot environment. A glare index below UGR-19 is acceptable and above UGR-25 is uncomfortable.

If the light source itself remains in the field of view and is bright, it can become a source of discomfort glare. Therefore it is best to position the light source behind the camera, either above or to the side. We can also reduce the effects of discomfort glare by increasing the task luminance relative to the luminance of the surroundings. Discomfort glare can also be reduced by: 1) decreasing the luminance of the light source, 2) diminishing the area of the light source, and 3) increasing the background luminance around the source if we can stop down the sensor aperture in this case.

IV. Intensity Control

To satisfy the visual comfort of machine eyes, apart from selecting proper types of light source and cameras, the key controllable parameters of a luminare are radiant intensity and geometrical pose in a practical vision system. The purpose of intensity control is to achieve proper image brightness which is in the range of the sensor, with linear property, and has contrast as high as possible. The purpose of pose control is to avoid possible glare and achieve uniform intensity distribution.

To control the image intensity so that it will concentrate on an optimal point, firstly the sensor sensitivity must be considered, then the image irradiance is estimated from source radiation to image sensing, and finally the optimal control point is decided.

A. Image Irradiance Estimation

The brightness that the camera perceived is the light intensity (energy level) and varies depending on the light color (wavelength). The distribution is quantified by a curve of the brightness sensation versus wavelength, called the luminosity curve. The sensor's spectral response is expressed as the three luminosity curves:

$$\rho_r = \rho_r(\lambda), \rho_g = \rho_g(\lambda), \text{and } \rho_b = \rho_b(\lambda)\,. \qquad (6)$$

To estimate the image irradiance, we need to analyze five procedures, i.e. source radiation, source efficiency, surface irradiance, surface reflection, and sensor perception. First, the total output radiation of a light source at temperature *T* is proportional to four times the temperature:

$$M_e = \varepsilon\sigma T^4, \qquad (7)$$

where σ is a constant and the emissivity $\varepsilon \in [0, 1]$ varies with wavelength.

According to *Planck's radiation law*, the spectral distribution of the radiation emitted by a blackbody can be described as a function of wavelength λ,

$$M(\lambda) = \frac{C_1}{\lambda^5}\frac{1}{e^{C_2/\lambda T} - 1} \qquad (8)$$

where C_1 and C_2 are two radiation constants.

The peak wavelength, λ_{max}, in nanometers, is given by

$$\lambda_{\max} = \frac{2.8978\times10^6}{T} = 2.8978\times10^6(\frac{\varepsilon\sigma}{i^2R})^{\frac{1}{4}}\,. \qquad (9)$$

Equation (9) depicts the power output of the light source and the spectral distribution of intensity at different temperatures. Obviously we can find that with increasing temperature, more energy is emitted and the peak emission shifts toward the shorter wavelengths.

Consider that the vision sensor is sensitive only to a portion of the electro-magnetic wave, i.e. $380<\lambda<750$ (nm). Due to the quantum efficiency of the vision sensor, the quantity of light as seen by the camera, i.e., is

$$M_e \int_{\lambda_1}^{\lambda_2} M(\lambda)d\lambda = \int_{380}^{750}\frac{C_1}{\lambda^5}[e^{\frac{C_2}{\lambda}(\frac{\varepsilon\sigma}{i^2R})^{\frac{1}{4}}} - 1]^{-1} d\lambda \qquad (10)$$

where W_e is the efficient light energy.

In the case of a 3-CCD camera, since the color temperature of the light source varies as long as the input power changes, the visible efficient energy becomes:

$$W_{r,g,b} = \int_{\lambda_1}^{\lambda_2} M(\lambda)\cdot\rho_{r,g,b}(\lambda)\cdot\eta(\phi)\cdot\varepsilon_{r,g,b}(\phi)d\lambda\,. \qquad (11)$$

On the other hand, we have

$$L = \int_{380}^{750}\frac{C_1}{\lambda^5}\frac{1}{e^{C_2/\lambda T} - 1}d\lambda \;\underline{\underline{x=\lambda T}}\; T^4\int_{380T}^{750T}\frac{C_1}{x^5}\frac{1}{e^{C_2/x} - 1}dx$$
$$= C(T)T^4\,. \qquad (12)$$

where

$$C(T) = \int_{380T}^{750T}\frac{C_1}{x^5}\frac{1}{e^{C_2/x} - 1}dx = \underset{\Delta x\to 0}{limit}\sum_{380T}^{750T}\frac{C_1}{x^5}\frac{1}{e^{C_2/x} - 1}\Delta x \qquad (13)$$

is defined as a coefficient function.

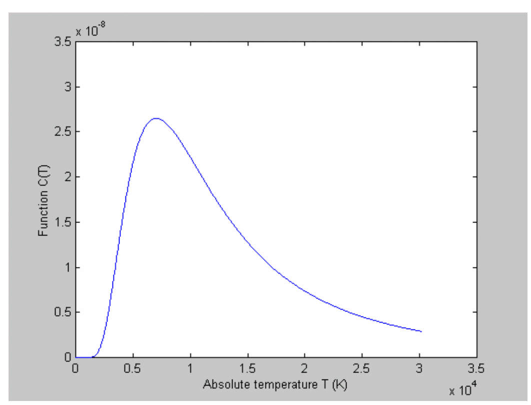

Fig. 1 Temperature vs coefficient ***C***(T)

Using numerical computation to solve (13), an example curve is illustrated in Fig. 1. Finally the luminous flux function (12) can be obtained.

On the other hand, the light emitted by a source is usually not uniformly distributed in all directions and the luminous intensity varies according to the position beneath the source. Manufacturers of luminaires usually provide intensity distribution diagrams for their products, which show the relationship between the luminous intensity and the angle to a reference position of 0^o situated vertically below the source. The polar graph is often used for these purposes. It can also be calibrated using the techniques of luminaire photometry developed by Lewin and John [7]. Finally the efficient energy distribution is modeled as:

$$L(\phi,\theta) = W_{r,g,b} \cdot \Gamma(\phi,\theta)\,, \qquad (14)$$

where the function $0 <= \Gamma(\phi,\theta) < 1$ describes the spatial distribution of source radiation.

Considering a point on the object surface, its irradiance is the integral of the whole angular distribution over a specified solid angle. The object surface then becomes another source and the image irradiance of the vision sensor can also be computed. Since real objects are usually not Lambertians, three parts contribute to the surface reflection, that is I_d (diffuse reflection), I_{s1} (gross specular reflection), and I_{s2} (specular reflection). Then the image irradiance of an object illuminated by a source is represented by a function as in [5].

B. Intensity Control

A camera usually has the requirement of minimum illumination which is typically 2 [lux] with high-gain operation. Theoretically, a camera's sensitivity could be increased as much as desired simply by increasing the amplifier gain and operating the CCDs at a lower output level. Of course, the SNR will degrade when this is done. That is what happens in a camera's "high gain" modes, which trade signal quality for sensitivity. On the other hand, the full-quality mode of a camera operates the CCDs at the light level given in the sensitivity specification. This may be somewhat of a trade-off with highlight performance.

The vision sensor often has best linearity between 15% and 90% of the output level. In fact, the illumination condition below 20% is unacceptable because: 1) low SNR for the existence of noise and dark current, 2) nonlinear quantization at this area, 3) nonlinearity because of gamma correction. An illumination condition above 90% output level is also unacceptable because of contrast compression of the knee slope and loss of color properties. Hence, the optimal setpoint of illumination intensity is at about 80% of the output level because of high SNR, linearity, and contrast.

The illumination intensity can be controlled in two ways: 1) phase-control to adjust the electrical current intensity using a dimmer; 2) pose-control to adjust the distance between object and luminaire using a robot end-effector. Usually it is better to keep the luminaires far away from the object because the illumination will be more uniform in this case and will increase image SNR. It is also better to keep the luminaire in full-on state because it entails a higher color rendering index in this condition and facilitates the obtaining of true surface information.

Machine vision applications have a great need for feedback control. The vision-illumination system can be considered a closed-loop system in which the vision sensor plays a second role as the feedback channel. The pose and dimmer phase are determined by a controller according to the visual feedback, source model, and optimal setpoint. The energy magnitude of source radiation and image irradiance may be estimated using the techniques discussed above.

V. Implementation

A typical system for illumination control usually includes a robot, manipulators of light source and vision sensors, an image processor, a system controller, and an object in scene. Here we focus on the control of the energy magnitude of source radiation, although other parameters may be discussed in future. The illumination control system is an active system with visual feedback. The goal is to keep the sensed object in a good illumination condition so that it will be beneficial to the further modeling processes. In our simulation system, a fuzzy-PID controller is used to adjust the parameters of illuminant.

A simulation system for illumination control was implemented with MATLAB (Fig. 2). The step response, sine response, zero input response, and random input response of the actively illuminated vision system have been observed, while we assume it has 10% environment light noise. Typically, step response happens when the robot stays in a dark room and a light is turned on at a certain time (Fig. 3). Sine response happens when the robot walks in an environment with periodically installed lights (Fig. 4), for example, a robot moving on a road as in Fig. 5.

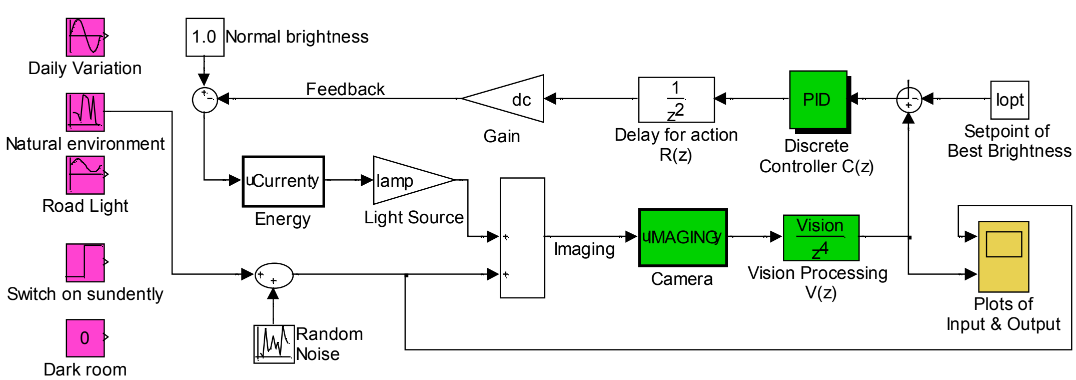

Fig. 2 The simulation system for illumination control

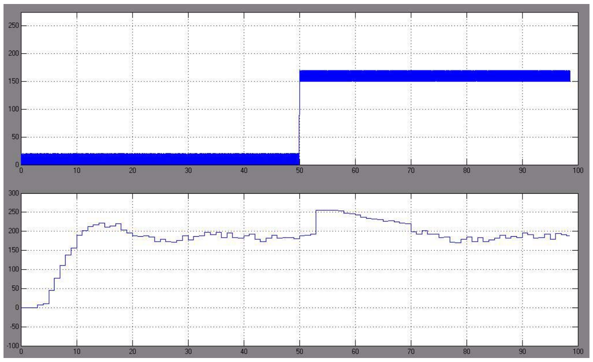

Fig. 3 Step response of the actively illuminated vision system, with 10% environment light noise. (It happens when the robot stays in a dark room and a light is turned on at a certain time.)

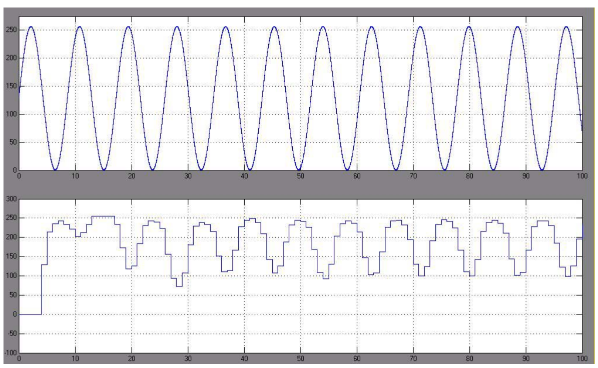

Fig. 4 Sine response of the actively illuminated vision system. (It happens when the robot walks in an environment with periodically installed lights, e.g. on a road as in Fig. 9.)

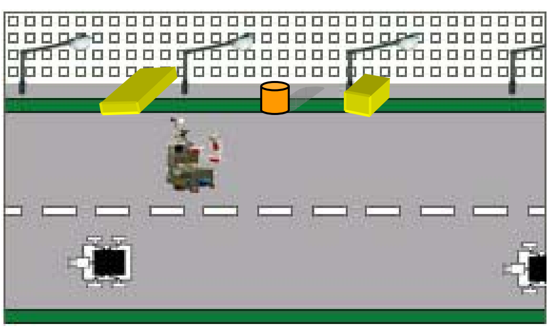

Fig. 5 A robot walking in a virtual environment with periodically installed lights.

VI. Conclusion

This paper presented an idea of active illumination control for the robot eye. Strategies are proposed to achieve optimal illumination conditions for vision sensors so that best quality images can be obtained with high SNR, contrast, color rending, and linearity. The controllable parameters include optical parameters and pose parameters of luminaire and sensor. The characteristics of a robot eye and its "comfort" conditions have been analyzed. The image intensity is theoretically controlled at a good setpoint. Glare avoidance methods are proposed for treating two types of glare, disability glare and discomfort glare. The disability glare can be eliminated by placements of light source, vision sensor, or targets. The discomfort glare is evaluated using the CIE-UGR criterion and can be diminished by control of source position, radiant flux, or background luminance. Further work is under way for implementation of the technology in practical applications.

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